COMPOSITE SMART MATERIALS FOR DEFENSE AND DUAL-USE APPLICATIONS

R & D STATUS REPORT
MML TM 95-04

Contract Number:	N00014-95-C-0037
Expiration Date:	June 23, 1997
Contract Amount:	$2,792,448
ARPA Order Number:	MDA972
CDRL Data Item Number:	A-113-1 DI-A-3002
Date:	April 12, 1995
Period Covered by this Report:	December 24, 1994 - April 10, 1995
Nomenclature of the System or Program:	Composite Smart Materials for Defense and Dual-Use Applications
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Name of the Issuing Government Agency:	Office of Naval Research Code 252A SMV Ballston Tower One 800 North Quincy Street Arlington, Virginia 22217-5660
Security Classification:	Unclassified
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DESCRIPTION OF PROGRESS

Summary:

During the past four months, we have:

- Set up the program
- Conducted a kick-off meeting
- Made substantial progress on Task 1 (Requirements Definition for Undersea Quieting)
- Initiated parts of Task 2 (Preliminary Material Requirements Definition)
- Presented two papers, one at the SPIE meeting in San Diego, CA, and one at the ONR Transducer Materials and Transducers Workshop, Pennsylvania State University

Progress is discussed in more detail below.

Task 1 — System Requirements

Top-level requirements and system-level designs have been developed during this reporting period. The top-level requirements for an echo canceling acoustic tile have been identified (Figure 1 and Table 1). The corresponding system-level design has been synthesized, in order to meet these requirements, using system-level simulations of the smart acoustic array geometry, control algorithms, sensor characteristics and far-field scattering effects from the composite tile (including the dead space between the radiating surfaces).

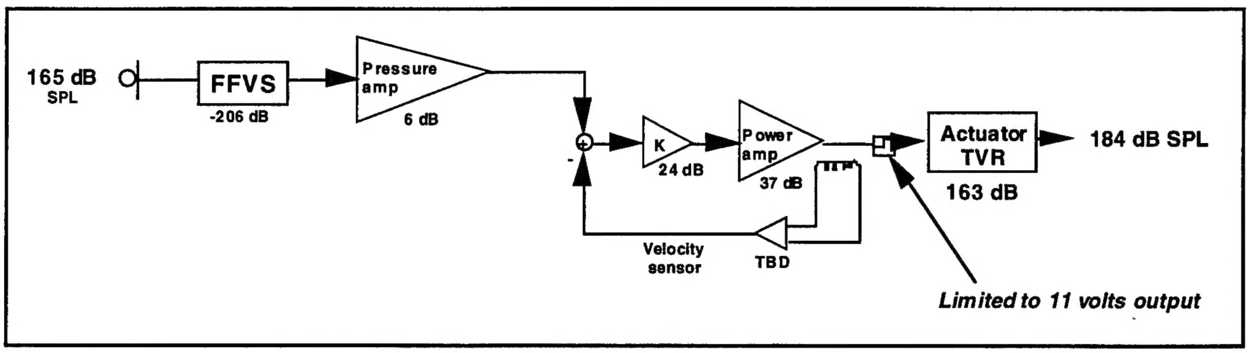

Figure 1. System gain allocations

Table 1. System impact

System Elements	System Gain	Design Driver	System Impact
Pressure sensor FFVS	> -206 dB	Magnitude/phase linearity	Velocity to pressure sensor matching
Controller pressure loop voltage gain	> 30 dB	Stability margins with uncertain sensor/actuator/amplifier transfer functions	Closed loop gain is critical to performance
Power amplifier voltage gain	> 37 dB	Power densities are thermally driven	Impacts max SPL
Actuator TVR at surface	> 163 dB	TVR, broadband operation	Determines SPL and frequency response of the tile
Total	24 dB		

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The important results from this requirements analysis and system design task include:

- Significant expected noise quieting technology improvements using smart materials technology has been identified.
- Realization that a 56% active surface area is necessary to meet top-level requirements, with actuator/sensor arrays that have no more than half trace wavelength spacing.
- Achieving an actuator array design with sufficient sound pressure level and acoustic efficiency, while remaining compatible with acoustic spacing and cost-effective manufacturing techniques, is challenging but achievable.
- Thermally driven designs of the power amplifiers will be necessary to maximize system performance. This result stems from the need for simple, local control architectures and maximizing the electrical power delivered to the actuators. The maximum sound pressure levels achievable by the acoustic tile will play an important role in determining at what stand-off ranges smart materials will be effective.
- A two-sensor, locally controlled cancellation design can achieve required performance, while allowing the actuator and power amplifier to have significant phase and amplitude variations.
- Sensor amplitude and phase characteristics will be critical to the overall system performance, based on the control architecture chosen.

Several system-level trade studies have been conducted, including control architectures and array geometries. These system-level trade studies have been driven by design concept studies that included: acoustic pressure sensor analysis, velocity sensor trade-offs, actuator design trade-offs, power amplifier design trade-offs, and matrix material investigations to improve thermal conductivity.

The results of the requirements analysis phase has been summarized in a draft CSM requirements document. This document describes the system-level performance of the acoustic tile and the required performance of the components within the tile. This document is currently under internal review.

To date, the following technical issues has been identified at the system level:

- Sensor Matching — Simulations show that the pressure sensor and the velocity sensor must be matched with respect to each other via the free-field acoustic impedance by approximately 0.5° in phase and 2 %in amplitude. Although this matching is at the average over the entire array, achieving this accuracy will be difficult. Prototyping the acoustic tile and measuring the sensor responses, and iterating the sensor construction with changes in the construction process, will lower the risk associated with the final demonstration.

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- Production Cost — The total cost for using smart materials for noise quieting is driven by two factors: the unit cost and the area coverage necessary for overall quieting. For the frequency ranges currently being considered, an underwater vehicle will probably need almost complete coverage of its external surface with the acoustic tiles to be effective. At the present time, the unit cost of the tile needs to be $1,000 in quantities of 30,000, which is believed to be feasible. With this unit cost, the material cost for applying the acoustic tile to a full-size submarine will be approximately $30,000. Further investigations are needed to determine if the unit cost is achievable, and if the material cost on a per-ship basis is acceptable. The unit cost analysis can be performed concurrent with the design process, while the total material cost can be discussed with Navy personnel.

- Electro-Magnetic Interference — Since the acoustic tile utilizes both DC and AC electric fields, there is a concern about the actuator drive field interfering with the sensor outputs. In addition, the tile itself will radiate some DC and AC electromagnetic energy into the water. To minimize EMI concerns between the actuator and the sensor, differential amplifiers will be used for the sensor signal conditioning. The radiated EMI concern will require more information from the Navy regarding acceptable levels as a function of frequency. Measurements of the acoustic tile can be made to assess its radiation level, although such tests are not presently planned.

Task 2— Application Specific Design Models

This task was incorporated into the requirements task report during the past 4 months. A certain amount of iteration has been required to determine, from already available information, whether initial requirements could be met. During the next period, NRL will begin to model the array to determine whether a random array will meet requirements, and the nature and number of sensors required.

We have begun to test available Navy models (TTOP and Chief) on the small, 100-actuator array built under the SMS program to determine their capability in modeling the performance of an array of sensors in a composite. Initial runs indicate that main lobe shape and level, as well as front to back ratios for the array, can be modeled to within 3-4 dB of measured values, but sidelobe predictions deviate by considerably more.

Task 3 — Early Focus Composite Constituent Development

Task 3.1 — Sensors:

The requirement for both a pressure and velocity sensor at the head of each element imposes an interconnection challenge. Experiments have been conducted to determine whether measuring the current to each actuator will give a sufficiently accurate estimation of the head velocity. The initial experiments indicated good qualitative agreement between current (compensated for the blocked capacitance) and velocity, but quantitatively the magnitude and phase relationship were not accurate enough. The fixture used for these experiments, however, had mutliple resonances and these must be removed before a final conclusion can be drawn.

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Task 3.2 — Actuator Design and Development (AVX):

The design elements in the critical path for the smart acoustic tile are the actuators and sensors. With their system requirements established by the system design discussed above, design and development is focused on actuator material, the size of individual actuators, and their internal (electrode) design to minimize clamping. This part of the effort is supported by MML•B in modeling stress in the various design candidates.

Suggested part styles are derived from standard AVX capacitor styles in order to benefit from existing fabrication and parts handling tooling. Part styles include 0805, 1206, 1210, and 1418, with 0.75-, 1- 1.5- and 2-mm active lengths, respectively. Note that part styles reference the nominal length and width of the device (i.e. 1210 indicates 120mils x 100mils cross section). Target displacement for all chips are 1-2μm at < 2MV/m drive voltage. Initial tasks are for design and analysis of actuators with low clamping stresses, and thus large displacement and good reliability, and for piezoelectric chip-style sensor evaluation.

A purchase order has been placed for ~100 kg of Type II piezoelectric (e.g., PZT5A). This will be the baseline composition for piezoelectric devices because of combined properties of relatively low dielectric constant (~1800), moderate loss tangent (~2%), moderate-to-high induced strain (d33~45-pC/N) and high Curie temperature (~360°C). This material is satisfactory for re-flow solder assembly methods without losing its polarity. Initial experiments with electrostrictive PMN will use both AVX's standard "actuator" formulation, optimized for near room temperature use, and a lower Tc material (Tc~20-30°C) which will have better performance at lower temperatures (~5-10°C) encountered in undersea applications.

We are fabricating variants of 1206 and 1210-style actuators with different sizes of inactive margins. These will be used to assess: a) effects of margins on uniformity of displacement across the top surface, and b) effects on the longevity of parts operated for extended periods with ac- and dc- voltage near 1 MV/m (or higher). Standard fired margins for these part styles (as for capacitors) are 200-250μm, and we are also making devices with larger (~300μm) and smaller (~150μm) margins. True "marginless" styles, i.e. with no side margins, will be fabricated at a later date, and these will have to be tested with an encapsulant due to the exposure of internal electrodes. Fabrication of devices with stress-relieving slots fired into the margin regions will also be made once artwork currently being designed is available.

Testing is being conducted to try to establish a correlation between observed variations in device resonance and possible internal defects. Piezoelectric and electrostrictive chips are being analyzed in an impedance analyzer, sorted according to resonance characteristics, and then destructively analyzed (polished cross-sections) to look for imperfections that may affect the resonance. Results to date are not conclusive. We are also using acoustic emission analysis to attempt to document the onset of micro cracking during a series of ac-voltage cycles with increasingly high amplitudes (up to 10 MV/m field strength). We have established equipment settings that give reproducible high-intensity acoustic events, but these have not yet been correlated to directly observed cracks in destructive analysis. However, we have observed in limited testing that PMN 1206 devices can develop microcracks when subjected to continuous dc-voltage of 3.5 MV/m for up to 1000 hours.

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Plans for the Next Reporting Period:

1) Artwork for the variable margin study has just been received. In the next month, PMN devices will be fabricated and fired. Testing for displacement uniformity will be started immediately and should produce some quick initial results. Life-testing will be started, but results will not be available for several weeks (at a minimum).

2) The piezoelectric powder should be received, and tape casting will start immediately. Green tape thickness will be targeted to yield fired layer thicknesses of ~20μm to meet system specifications of 10V drive levels.

3) Acoustic emission testing will continue.

Issues/Concerns:

1) Does the scope of work for VPI allow for help with imaging the displacement uniformity of the top surface of single actuators? If so, devices will be provided to them for testing.

2) System designers at MML•B have requested integral velocity sensors on the top of the actuators. This requirement is very challenging in two respects: a) low-cost device fabrication, and b) design approaches with respect to cross-talk. We are considering several possible approaches (none of which are fully satisfactory at this time) which can be reviewed at the next technical meeting. Subsequent to technical discussions regarding capabilities and requirements, surviving designs will be prototyped.

Task 3.3 — Matrix and Reinforcement:

We are investigating materials with high thermal conductivity for encapsulation of power supplies.

Task 3.4 — Processors:

Preliminary estimates of required performance have been done as part of the requirements definition.

Task 3.5 — Controls:

Preliminary estimates of stability margins and required gains have been made as part of the requirements definition.

Task 3.6 — Power Supply Design and Development (VPT):

There is no detailed power supply design as yet. Power supply requirements are being iterated through the system design task. The current issue of greatest significance is the dissipation of heat. This is dependent on the thermal conductivity of the encapsulating polymer material. MML•B is currently identifying alternatives to traditional urethanes or RTV, as these have approximately one fifth of the thermal conductivity required.

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Task 3.7 — Actuator/Sensor Modeling:

A baseline design for the actuator has been chosen. The actuator has overall dimensions of 4.6 mm x 3.6 mm x 2.1 mm. It has 93 active layers, each 21 microns thick and 2 inactive cover layers, each 60 microns thick. The actuator will be made using surface-mount capacitor fabrication method and hence has relatively large inactive areas. The inactive areas lead to clamping of the actuators. We are building both 2-D and 3-D models of the actuators to calculate the displacements and internal stresses.

Major Items Purchased or Constructed during the Reporting Period

None

Changes in Key Personnel

None

Summary of Substantive Information from Trips, Meetings or Special Conferences

Dr. Stephen Winzer and Dr. Keith Bridger attended the ONR Transducer Materials and Transducers Workshop at The Pennsylvania State University on April 4-6. Dr. Winzer presented a poster on the Composite Smart Materials program. The poster led to several contacts with information on the undersea quieting application. Discussions were also conducted with W. Smith and Kam Ng on Guidance and Control applications for the composite smart materials. Dr. Winzer will visit Kam Ng at ONR for discussions on requirements.

Representatives from the team will attend the Acoustic Velocity Sensor Focused Workshop being developed by M. Berliner and J. Lindberg under sponsorship from ONR, NUWC and the Acoustical Society of America.

Summary of Problem Areas

None

Sufficiency of Effort to meet Contract Requirements

The effort appears sufficient at this time.

Fiscal Status

- Amount currently provided on contract: $1,825,000
- Expenditures and commitments to date: $ 652,451
- Funds required to complete work: $2,139,997

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